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Hygrothermal modeling and evaluation of freeze-thaw damage risk of masonry walls retrofitted with internal insulation

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ABSTRACT

For historical buildings with a worth-preserving appearance, internal wall insulation can be the only possible solution to improve the building energy efficiency. However, the application of an internal insulation layer changes significantly the hygrothermal performance of the building envelope. For masonry walls, such intervention may lead to freeze-thaw damage of the brickwork. In this study, a hygrothermal model is developed. The model takes into account moisture and heat transport in porous medium and tracks the occurrence of freezing and thawing in function of pore size distribution and as well as the ice content. Freezing and melting of water in porous medium is implemented based on the theory of freezing point depression, as freezing temperature of water in porous medium depends on pore size, *i.e.* water in the smaller pores freezes at temperatures lower than 0 °C. The numerical model results are compared with a porous medium freezing experiment and good agreement is found. Traditional hygrothermal assessment uses the number of zero crossings on a Celsius scale as the number of freeze-thaw cycles. We propose a method that uses the number of actual ice growth and melt cycles as an indicator more accurately accounting for the freeze-thaw process. In addition, we develop an index, called FTDR Index, to assess freeze-thaw damage risk. We perform simulations of uninsulated and internally retrofitted masonry walls using two Swiss climatic conditions. The study clearly shows increase of freeze-thaw cycles and ice content after internal retrofitting in both climates. Thus, FTDR Index increases after internal retrofitting.

1. Introduction

Energy efficiency in buildings can be improved by retrofitting masonry walls with internal or external insulation. For historical buildings with a worth-preserving appearance, internal wall insulation is the main retrofit solution to consider in order to improve building energy efficiency. However, internal thermal insulation changes significantly the hygrothermal performance of the building envelope [1]. In particular, the addition of insulation to the inside of load-bearing masonry walls may cause performance and durability problems of individual components or whole systems, such as the initiation of freeze-thaw damage of the facing brickwork. As the added insulation reduces the heat flux from the interior into the insulation, the wall drying ability decreases, leading to increased moisture levels and decreased temperature in the masonry walls. This is the main cause of freeze-thaw damage problems resulting from internal retrofitting. Professionals and building owners may avoid internal insulation solutions due to the difficulty to assess the increased risks of freeze-thaw damage. Therefore, it is essential to provide a mode of analysis of the eventual risk of freeze-thaw damage in masonry walls subjected to inside internal retrofitting.

The primary mechanism responsible for freeze-thaw damage is the expansion of water when the liquid changes to ice [2]. In porous medium, the volumetric expansion of water by 9% due to freezing exerts tensile stresses on the material matrix and causes damage when the stresses exceed the strength of the material [3–5]. One approach is the use of the number of freeze-thaw cycles to estimate the potential for freeze-thaw damage [6]. However, such studies often use the number of zero crossings on a Celsius scale as the number of freeze-thaw cycles [6–9]. This approach fails to consider that water in porous medium freezes at temperature below 0 °C,

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varying in function of the pore size. The water in the smaller pores freezes at much lower temperatures, so that liquid water can be preserved well below 0 °C. From thermodynamic principles, the freezing point is the temperature where the free energy of water in the porous medium is equal to that of ice. The free energy of water in porous medium can be affected by capillarity, adsorption and dissolved salts. The capillary pressure is inversely proportional to the pore size. Therefore, the smaller the pore size, the larger the capillary pressure.

Previous research has shown that freezing is not necessarily damaging to porous medium and the most important factor for freeze-thaw damage is degree of saturation of moisture content at the time of freezing [10–13]. The degree of saturation is defined as the ratio of actual moisture content to moisture content at saturation. The critical degree of saturation is widely used in literature to define a porous material resistance to freeze-thaw damage [13–15]. At moisture contents above critical degree of saturation, the porous material will be seriously damaged by freezing. Prick [15] reported the critical degree of saturation of ten French limestones to be between 0.58 and 1.0. Mensinga et al. [13] reported that the critical degree of saturation for three Canadian bricks is between 0.25 and 0.87. Additionally, the frost durability of porous medium is affected by pore size distribution and porosity. High porosity reduces the frost resistance of bricks while small pores are more dangerous to freeze-thaw damage than bigger pores. Maage [16] developed an empirical mathematical correlation between frost resistance and pore characteristics.

Field observations of freeze-thaw damage in clay masonry structures suggest that the performance of bricks is affected not only by the materials characteristics but also to the microenvironment in which they are exposed [17]. Factors such as geographical location, direction of exposure versus rain or sun, season of the year affect moisture content in the masonry wall. The most likely meteorological condition for freeze-thaw damage is a substantial temperature drop below 0 °C with a significant amount of rainfall in the previous days. Liso et al. [5] developed a frost decay exposure index based on number of freezing events and rainfall sums prior to freezing events to provide a geographically-dependent freeze-thaw damage risk assessment.

Hygrothermal models, simulating coupled heat and moisture transport, have the ability to assess long-term heat and moisture performance of wall assemblies and predict risks of moisture related problems [18–20]. They are suitable to analyze the changes in hygrothermal performance after adding insulation layer to masonry walls. However, traditional hygrothermal models used for investigating the risk of freeze-thaw damage do not model the process of freezing and thawing of moisture in porous medium [7,8]. It is yet not known whether it is appropriate to apply those models for studying freeze-thaw damage risk problems.

The objective of this paper is to assess the influence of internal insulation retrofitting on freeze-thaw damage risk of masonry wall assemblies. A hygrothermal model which can account for moisture and heat transport in a porous medium and track locally the occurrence of freezing and thawing in function of pore size distribution is developed in this study. The numerical model is validated using a porous medium freezing experiment. A new assessment method is proposed to indicate freeze-thaw cycles. In addition, a new index is proposed to evaluate risk of freeze-thaw damage. We perform simulations of the hygrothermal performance of base and retrofitted masonry walls for two Swiss climatic conditions. The number of ice content and freeze-thaw cycles occurring in the uninsulated and in the retrofitted masonry walls are compared.

2. Hygrothermal simulation model

2.1. Coupled moisture and heat transport model for freezing porous medium

The equations are based on the following hypotheses: (1) the porous media are non-deformable and no volume change occurs during freezing and thawing; (2) there is no salt present in the porous medium; (3) there is an analogy between capillary pressure curve (the relationship between capillary pressure and moisture content) and freezing curve (the relationship between subzero temperature and unfrozen liquid water content). If a solute is considered to be present in the porous medium, the melting point of water in porous medium will be further depressed. The freezing point depression depends also on the concentration of the solutes. In reality, the porous medium is deformable and volume changes occur during freezing and thawing. Since the volume change for bricks is small, the influence of volume change on the freezing process can be neglected.

In a porous medium under freezing, moisture may exist in the form of vapor, liquid and ice. Thus, the conservation equations for moisture transport in freezing and non-freezing porous media can be written for:

Water vapor:

$$\frac{\partial w_v}{\partial t} + \nabla \cdot g_v = -G_{l,v} - G_{i,v} \tag{1}$$

where w_v is the vapor content (kg/m^3); g_v is the vapor flow rate (kg/m^{2}s); $G_{l,v}$ is the moisture exchange rate between liquid water and vapor (kg/m^{3}s); $G_{i,v}$ is the moisture exchange rate between vapor and ice (kg/m^{3}s).

Liquid water:

$$\frac{\partial w_l}{\partial t} + \nabla \cdot g_l = G_{l,i} + G_{l,v} \tag{2}$$

where w_l is the liquid water content (kg/m^3); g_l is the liquid flow rate (kg/m^{2}s); $G_{l,i}$ is the moisture exchange rate between liquid water and ice (kg/m^{3}s); $G_{l,v}$ is the moisture exchange rate between liquid water and vapor (kg/m^{3}s).

Ice:

$$\frac{\partial w_i}{\partial t} + \nabla \cdot g_i = -G_{i,l} + G_{i,v} \tag{3}$$

where w_i is the ice content (kg/m^3); g_i is the ice flow rate (kg/m^{2}s); $G_{i,l}$ is the moisture exchange rate between ice and water vapor (kg/m^{3}s); $G_{i,v}$ is the moisture exchange rate between ice and water vapor (kg/m^{3}s).

The ice phase is considered immobile and thus g_i is equal to 0. Summing up Eqs. (1)–(3) leads to the balance equation of the total moisture transport:

$$\frac{\partial w_l}{\partial t} + \frac{\partial w_i}{\partial t} + \frac{\partial w_v}{\partial t} + \nabla \cdot g_l + \nabla \cdot g_v = 0 \tag{4}$$

As $\frac{\partial w_v}{\partial t}$ is much smaller than $\frac{\partial w_l}{\partial t}$ and $\frac{\partial w_i}{\partial t}$, the change in water vapor content is neglected. Eq. (4) can thus be simplified as:

$$\frac{\partial w_t}{\partial t} + \nabla \cdot g_l + \nabla \cdot g_v = 0 \tag{5}$$